# Design consideration for 100 kg cryogenic CaMoO4 detector

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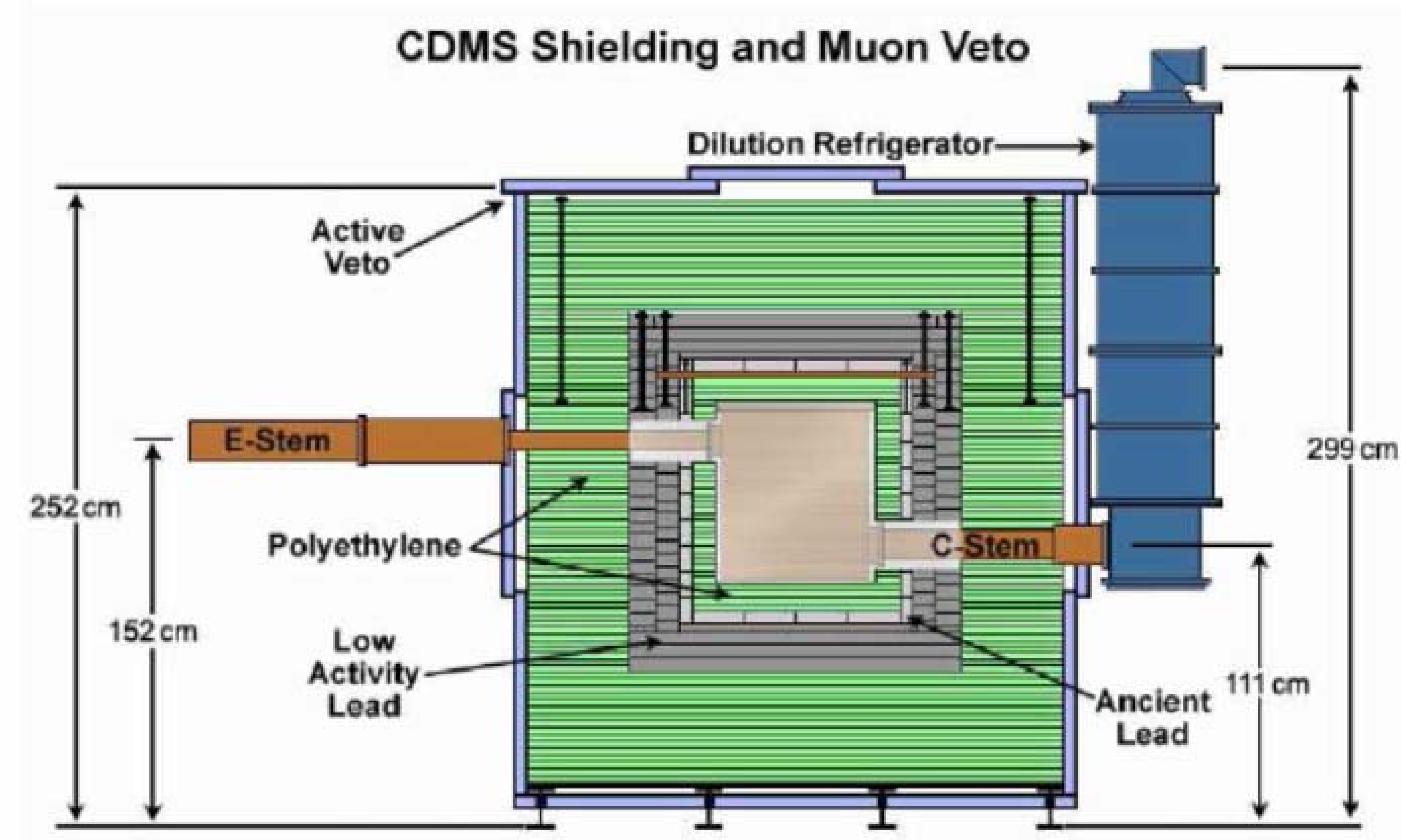
Oct/08/2010

2nd International Workshop on Double Beta Decay Search

# Cryogenic design in CDMS




CDMS: Tobias Bruch, thesis, 2010, P58 .

# Cryostat options

- Construct a dilution refrigerator using radio-pure materials.
  - × Cryostat very tall.
  - × Muon veto very large.
- A cryostat connected to a standard fridge from the shield.
  - Hang below the fridge. Some of the cold layers include shielding.
    - ✓ Straightforward cooling.
    - × Same height and veto problems. Muon veto has a large hole on the top.
  - ➢ Extend sideways from the fridge.
    - ✓ Flexible in inspection and easy to fit usual space.
    - ✓ Eliminates the need for most of standard and radioactive materials.
    - × Need a horizontal stem for the cooling power.

I'll use CDMS sideway design as an example.

# Design issues

- How to use radio-pure materials to replace impure materials?
- How much space for detectors?
- Space for amplifier components at 4K.
- How to wire from 4K to room temperature?
- How to accommodate thermal contractions as the system cools?
- The cooling power and temperature.

  - We are using 5cm(ϕ) x 5cm(h) CaMoO4 crystal= 500g weight
  - 100 kg $CaMoO_4 \Rightarrow$ 30cm(ϕ) x 30 cm(h) solid crystal space.
  - We can use 50 cm(ϕ) x 50 cm(h) for safety.

# Avoid radioactive contamination

(brass screws contains lead, stainless steel contains $^{60}Co$, Aluminum wall contains $^{40}K$, brazing material silver contains long lived isotopes, indium sealing beta decays.)

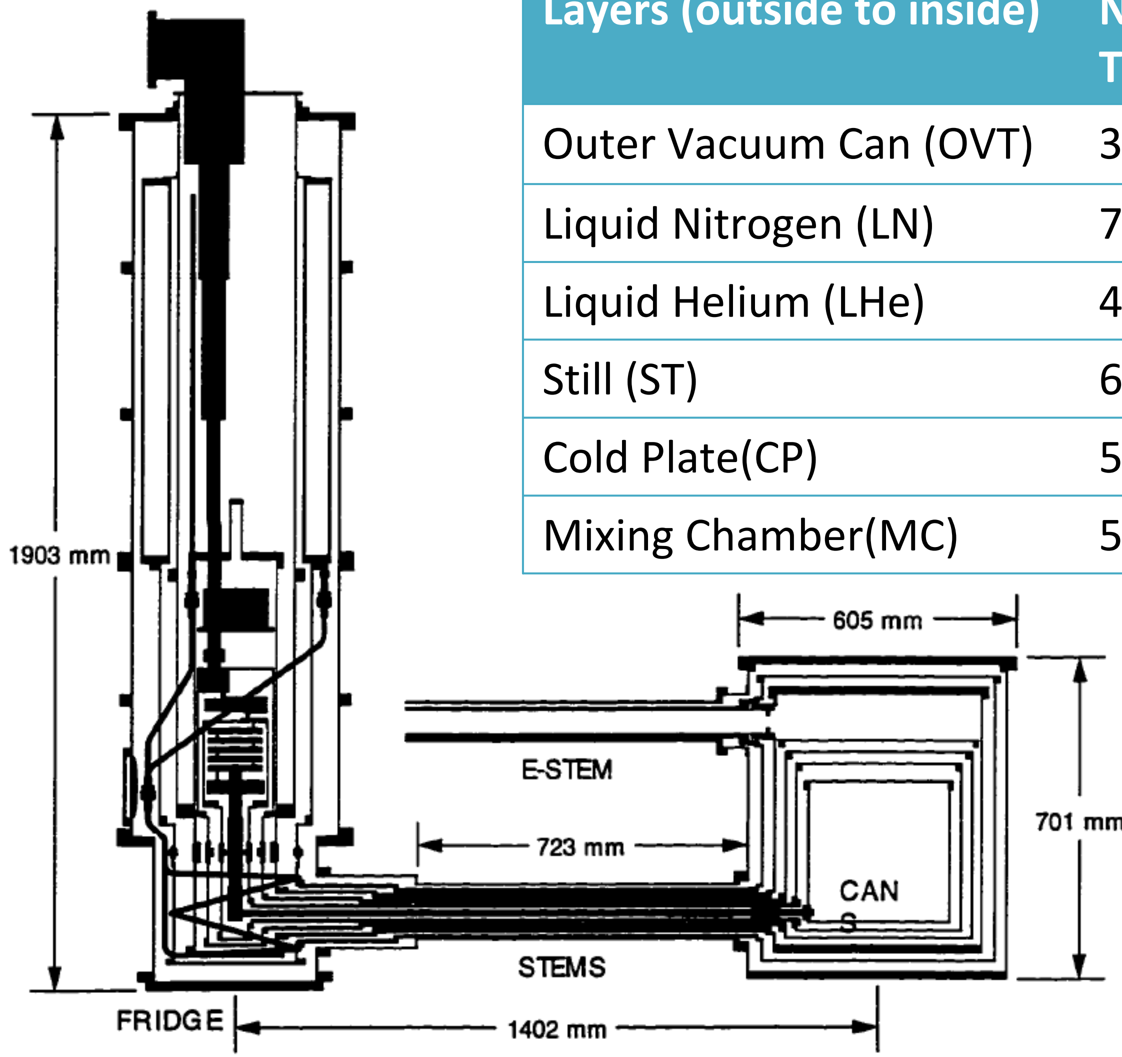
Copper is the only standard cryogenic material to use.

Ways to eliminate radioactive materials of the box:

- Electron weld all joints in the stems and cans. Apply finishing from larger size to final size.
- Use copper flanges with threads made by forming, not cutting.
- Use all copper sealing system. A rounded nose sealing design to avoid the use of indium which beta decays.

# CDMS Layout

| Layers (outside to inside) | Nominal Temperature | Expected Temperature |
|---|---|---|
| Outer Vacuum Can (OVT) | 300 K | 300 K |
| Liquid Nitrogen (LN) | 77 K | 100 K |
| Liquid Helium (LHe) | 4.2 K | 9K |
| Still (ST) | 600 mK | 900 mK |
| Cold Plate(CP) | 50 mK | 100 mK |
| Mixing Chamber(MC) | 5 mK | 10 mK |

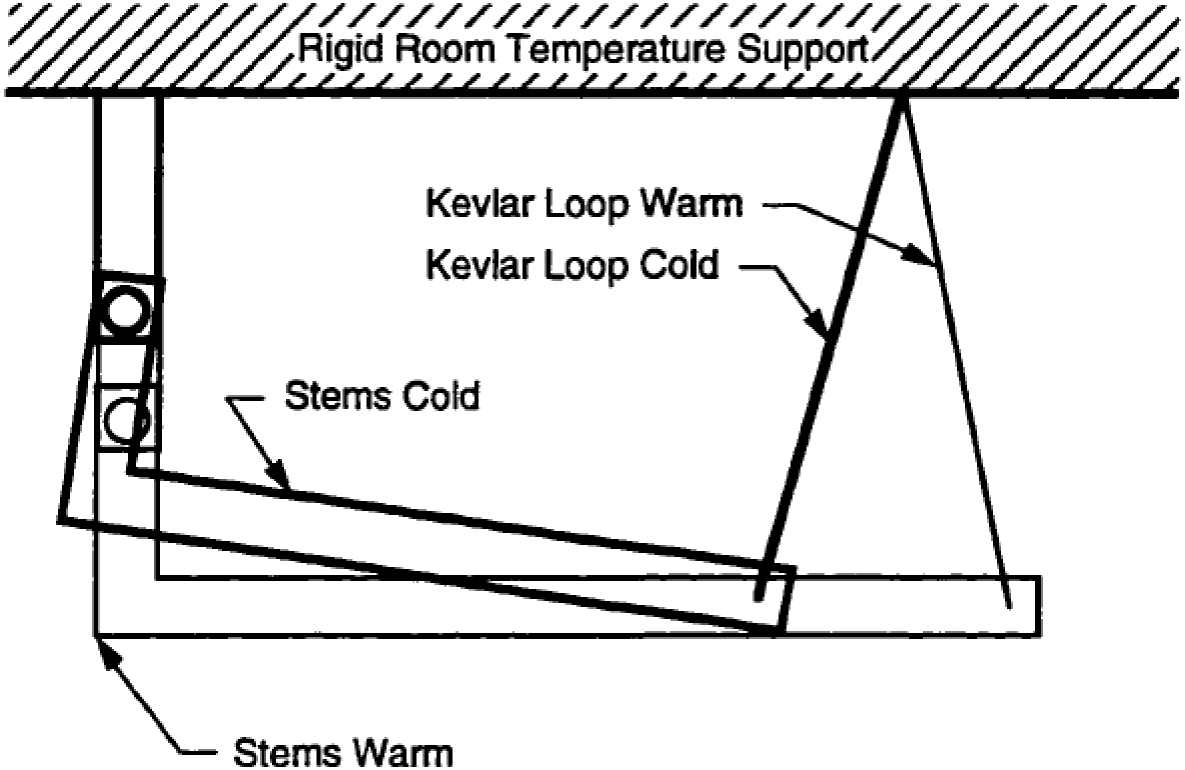



Boxes

# Porch Swing for supporting

Accommodates thermal contraction.

No need to find legs with low thermal conductance for the boxes to stand on.




Stem itself also need a section that can extend.

# Thermal model

Total power P conducted through a cross section A at temperature T:

$$Pdz = A\kappa(T)dT$$

Thermal conductivity

Integrate $\Rightarrow$

Power P, conducted from temperature $T_2$ to $T_1$ by an object of cross section A and length L

$$P = \frac{A}{L}\left[K(T_2) - K(T_1)\right]$$

$$K(T) \equiv \int_0^T \kappa(T)dT$$

# Example: Support material for cans

Support material should be mechanically adequate but not very conductive.

The required cross section A to support a mass M:

Safety factor

$$A = \frac{Mgf}{S}$$

Yield point stress

$$\Rightarrow \qquad P = \frac{K(T_2) - K(T_1)}{S} f \cdot \frac{Mg}{L}$$

Material quality factor q:

$$q = \frac{f}{S}\left[K(T_2) - K(T_1)\right]$$

# Mechanical Properties and quality factor

Mechanical Properties:

| Material | Yield Point Stress $S$ (MPa) | Young's Modulus $Y$ (GPa) | Safety Factor $f$ | $S/f$ (MPa) |
|---|---|---|---|---|
| Pure Titanium | 485 | 116 | 1.43 | 339 |
| Titanium Alloy | 830 | 150 | 1.43 | 580 |
| Vespel | 86.2 | 3.79 | 3.5 | 24.6 |
| Kapton | 34 | 6 | 3.5 | 9.71 |
| Kevlar | >724 | 60 | 3.5 | >207 |
| Stainless Steel | 520 | 210 | 1.43 | 364 |

Quality factor:

| Material | Temperature Ranges | | | | |
|---|---|---|---|---|---|
| | 300–88 K | 92–7.8 K | 8.6–0.86 K | 870–57 mK | 57–6.4 mK |
| Multiplier | 1 | 1 | $10^{-3}$ | $10^{-6}$ | $10^{-9}$ |
| Pure Titanium | 13 | 4.4 | 65 | 670 | 2800 |
| Titanium Alloy | 2.4 | 0.49 | 6.9 | 71 | 300 |
| Vespel | 3.3 | 0.55 | 3.8 | 24 | 59 |
| Kapton | 8.4 | 1.4 | 9.6 | 61 | 150 |
| Kevlar | 0.97 | 0.26 | 1.0 | 2.7 | 2.3 |
| Stainless Steel | 7.8 | 1.4 | 12 | 120 | 530 |

# Blackbody Radiation

Thermal power density transmitted from a warm surface ($T_h$) to a colder surface ($T_c$) is:

Stefan-Boltzmann constant 56.7 nW/(m$^2$ K$^4$)

$$\mathcal{P} = \sigma f(\varepsilon)(T_h^4 - T_c^4)$$

Geometry function of emmissitivity

For a vacuum between two parallel plates: $$f(\varepsilon_h, \varepsilon_c) = \frac{1}{\frac{1}{\varepsilon_h} + \frac{1}{\varepsilon_c} - 1} \approx \frac{\varepsilon}{2}$$

Between 300K and 77K, ε=0.02 $\Rightarrow$ $$\mathcal{P} = 4.619 \text{ W/m}^2$$

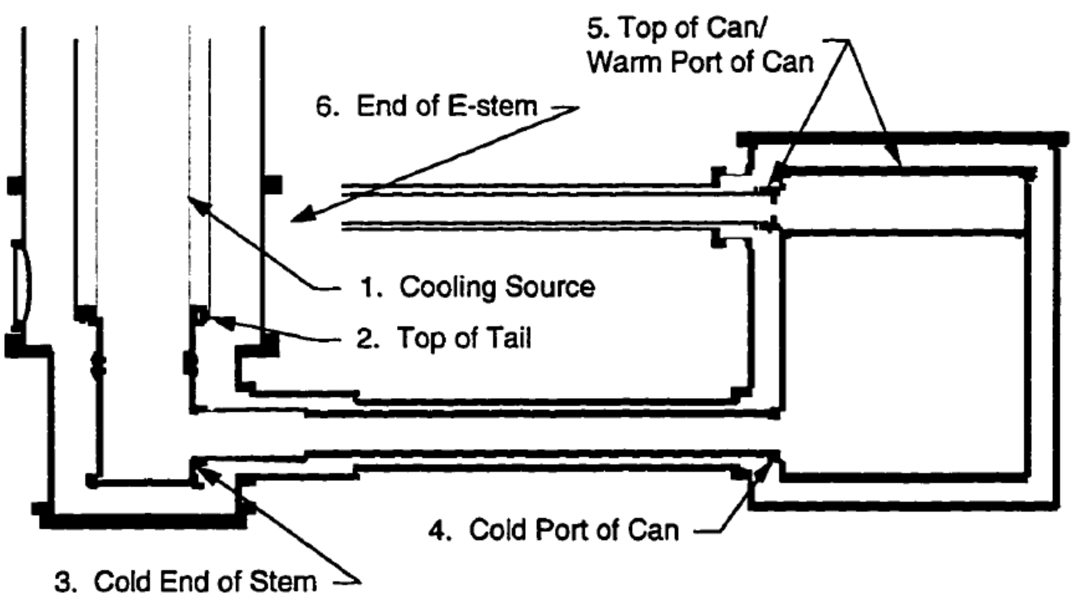
Extend the formula to multilayer insulation system.

# Modeling for the whole system

- A series of cylinders, connected end-to-end.
- Distributed power input: back-body radiation.
- Localized power input:  from supports, from radiation on the top and bottom of box cans.
- Assumptions: emissivity of the surfaces, the resistance of joints, thermal conductivity of materials.
- Pessimistic assumptions whenever possible.
- Discrete temperature jump in joints calculated from the electrical resistance.
- Use iterative procedure, starting from calculating integrated power density for each system.
- Include power dissipated by detector amplifier.

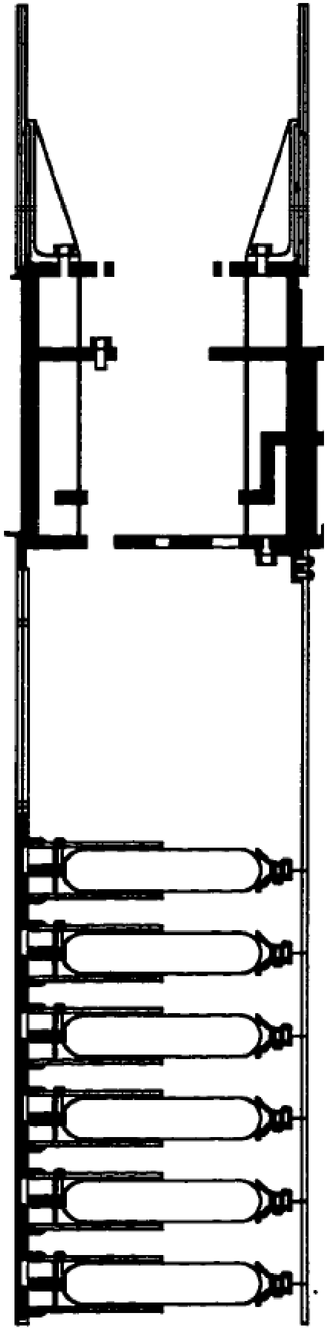
# Predictions of the thermal Model

| Location | Temperature on Layer at Location | | | | |
|---|---|---|---|---|---|
| | (K) | | | (mK) | |
| | LN | LHe | ST | CP | MC |
| 1. Cooling Source | 77 | 4.2 | 0.60 | 50 | 5.0 |
| 2. Top of Tail | 78 | 4.2 | 0.71 | 53 | 5.1 |
| 3. Cold End of Stem | 78 | 5.3 | 0.81 | 55 | 5.2 |
| 4. Cold Port of Can | 88 | 7.8 | 0.86 | 57 | 6.4 |
| 5. Top of Can/ Warm Port of Can | 92 | 8.6 | 0.87 | 57 | 6.4 |
| 6. Last Cold Point in E-stem | 114 | 26 | | | |
| **Total Power** | **36 W** | **0.97 W** | **1.4 mW** | **2.5 μW** | **38 nW** |



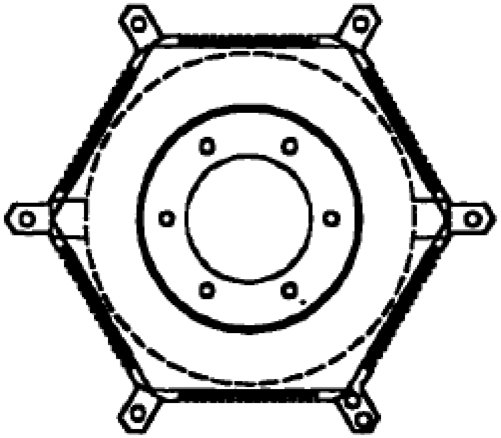
# Actual temperatures

| Location | Temperature on Layer at Location | | | | |
|---|---|---|---|---|---|
| | (K) | | | (mK) | |
| | LN | LHe | ST | CP | MC |
| 1. Cooling Source | 77.91 | | 0.637 | 39.2 | 7.54 |
| 2. Top of Tail | 78.59 | 4.07 | 0.641 | 36.6 | 7.54 |
| 3. Cold End of Stem | 80.90 | 4.55 | 0.488 | 49.1 | 7.86 |
| 4. Cold Port of Can | 88.39 | 5.36 | 0.435 | 40.5 | 10.9 |
| 5. Top of Can/ Warm Port of Can | 90.50 | 5.3 | 0.497 | 39.5 | 11.0 |
| 6. Last Cold Point in E-stem | 108.52 | 7.3 | | | |



# Detector assembly

•A detector package should include all supports, wiring, and heat sinking, can be tested as an assembly.
•Efficient use of available volume in the box.
•Close packing between detector modules can maximize the benefit of multiple scattering.



•Use graphite as mechanical support between floors.
•Wire are heat sunk at every stage.
•Wire from LHe to MC has no dielectric and exposed in vacuum to avoid static surface charge.

# Wiedemann-Franz Law

Free electron Fermi gas model: proportionality in thermal and electrical conductivity

Thermal conductivity

Electrical conductivity

$$\kappa(T) = \mathcal{L} T \sigma(T)$$

Lorentz number $\mathcal{L} = \dfrac{\pi^2 k_B^2}{3e^2} = 24.43 \dfrac{\text{nW}\,\Omega}{\text{K}^2}$

Power

$$PR = P \cdot \int_{z_1}^{z_2} \frac{1}{A\sigma} dz = \int_{T_1}^{T_2} \frac{\kappa(T)}{\sigma(T)} dT = \frac{\mathcal{L}}{2}(T_2^2 - T_1^2)$$

Resistance

If W-F holds, **a given resistance implies a fixed power**, independent of material.

W-F overestimates thermal conductivity in intermediate temperature range due to inelastic scattering with phonon.

# Wire heat loads (low temperature)

$$N_{\mathrm{eff}} = N / R \ (\mathrm{wires}/\Omega)$$

Heat load

For $N_{eff}$ = 700 (1/Ω)

| Temperature Range | $(PR)$ | $N_{Eff}(PR)$ |
|---|---|---|
| 9 – 0.9 K | 0.98 μW Ω | 0.69 mW |
| 900 – 60 mK | 9.8 nW Ω | 6.9 μW |
| 60 – 5 mK | 44 pW Ω | 31 nW |

Superconducting wire reduces the thermal conductivity by a large factor (e.g. NbTi Wiring)

| Cold End Temperature | NbTi Wiring |
|---|---|
| 0.9 K | 0.28 mW |
| 60 mK | – |
| 5 mK A | 0.18 μW |

For 300K to 9K range, we can use the W-F relation.

# Wire head load (300K to 9K)

(PR) values in **mW·Ω** for Copper and Gold from 300K to 9K

W-F applies

| Material | Temperature Range | |
|---|---|---|
| | 300 K–115 K | 115 K–9 K |
| Copper | 0.838 | 0.157 |
| Gold | 0.918 | 0.138 |
| Wiedemann-Franz | 0.937 | 0.160 |

Suppose the wire heat load less than 1/10 of that from cryostat modeling.

Trace contribute 2/3 of the total heat load. (Other 1/3 assigned to dielectrics.)

CDMS has 2200 wire traces.

Example in LN layer: Total power = **36W** in cryostat model.

- For each trace, allowed power p = 1/10 · 1/2200 · 2/3 · 36 = **1.08 mW.**
- Then, resistance for each trace should be grater than **0.87 Ω.**
- Using same method, resistance for each should > **5.5 Ω** in (115-9) K section.

# Issues not covered

- Cold Finger joints.
- The tail hinge and cold finger flex section.
- High Conductivity Copper wire for the thermal links to fridge.
- All copper vacuum seals.
- Physical wiring design (stripline design).
- Monitor system.
    - Thermometers.
    - Position sensors.
    - Touch sensors.
    - Fridge operation sensors.
- **Multiplexer to reduce the number of wires.**
- Detector shielding.

# Summary

- Sideway cryostat design issues discussed.
  - Accommodate contraction in low temperature.
- Establish a thermal model in basic layout.
  - Power load in different layers.
  - Minimum wire resistance from thermal conduction constraint.
- Using radio-pure materials.
- Still many more issues to consider.

# BACKUP

# CRESST-II cryostat